Review of recent theoretical developments in Higgs physics

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Xth Quark Confinement and the Hadron Spectrum
Munich, October 2012

Argonne
NATIONAL LABORATORY

After the euphoria

- Three months ago, the announcement of the Higgs discovery generated great excitement

- With the excitement over (or at least reduced), it's now time to analyze the discovery

- Is it the Standard Model Higgs, or do its couplings deviate?

- In fact, is it even a Higgs boson, or could it be something else (a spin-2 state, or a CP-odd scalar, or …)?

- Is theory in shape to distinguish between these possibilities?
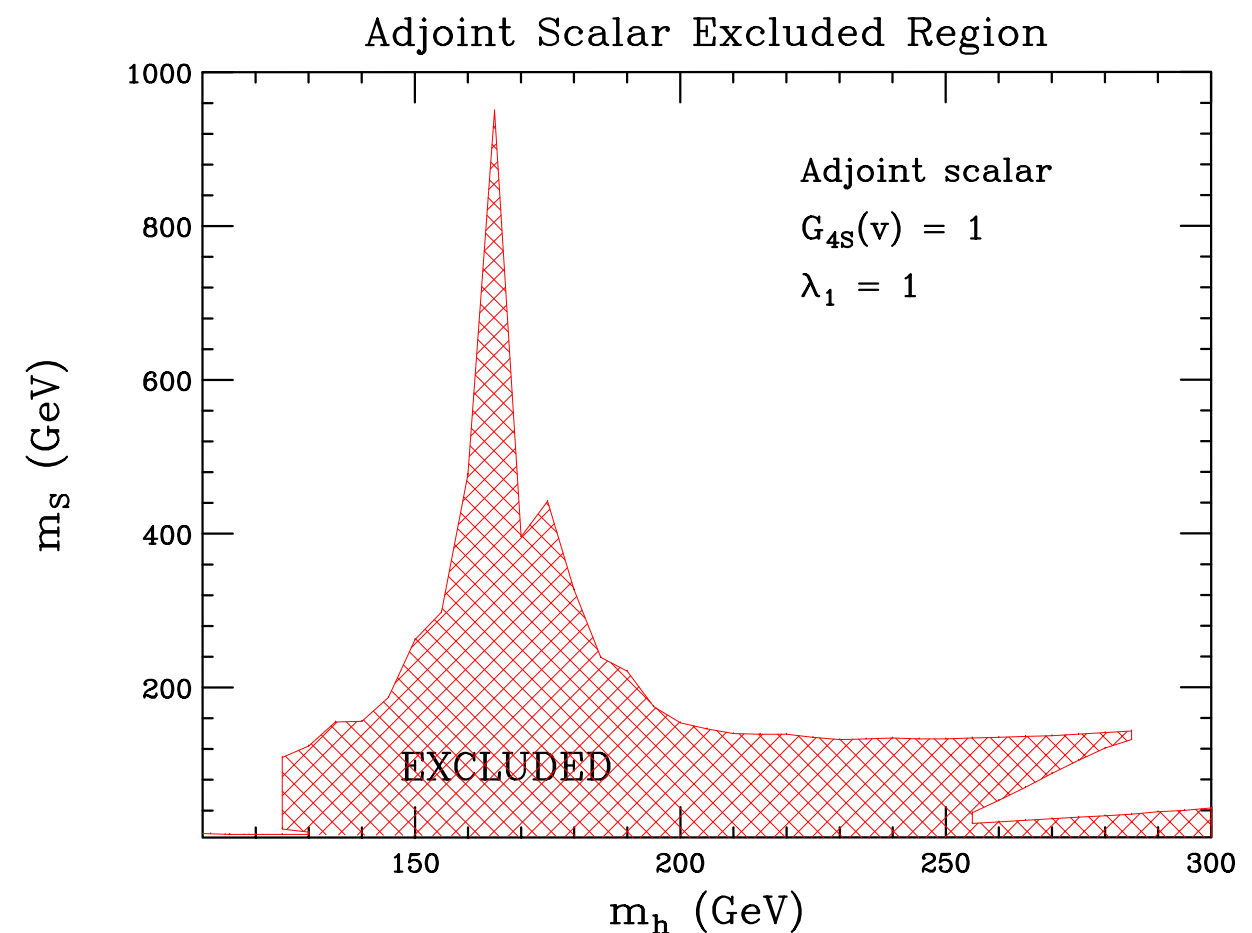
Discovery is the beginning

C. Grojean

Narrowing down the possibilities

- Current measurements already strongly constrain what SM extensions are possible
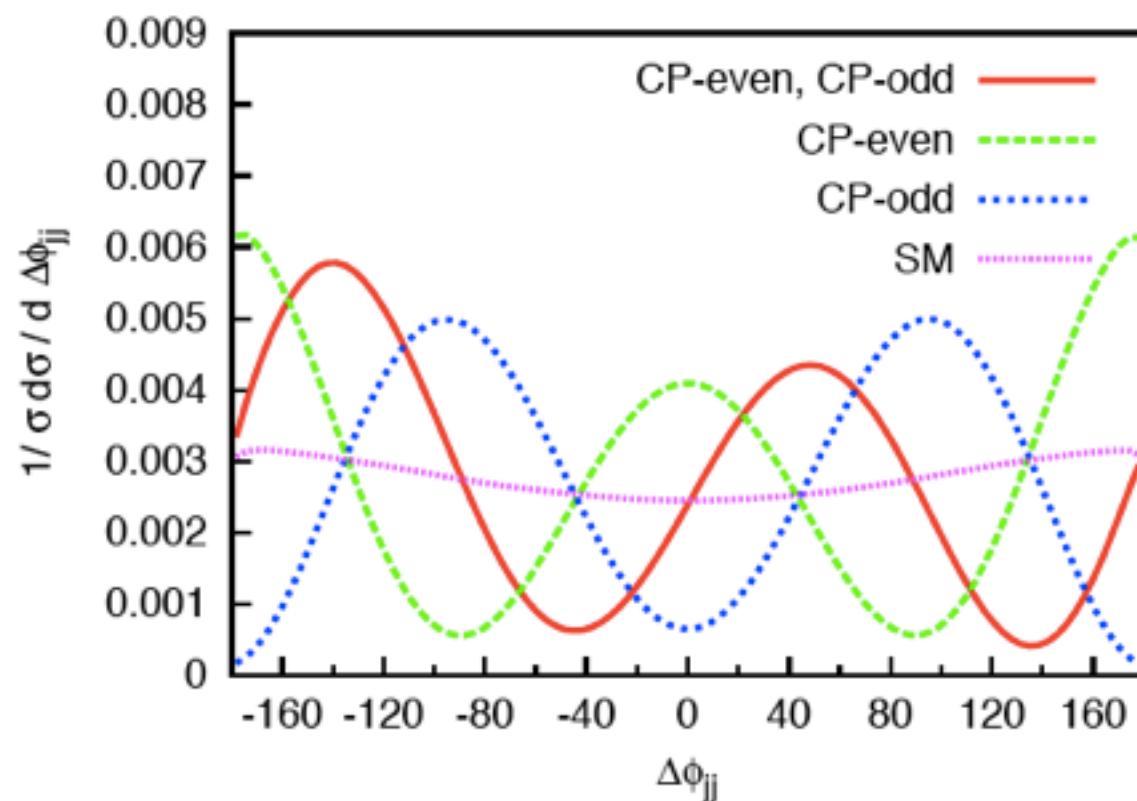

SM4, $m_H = 125$ GeV
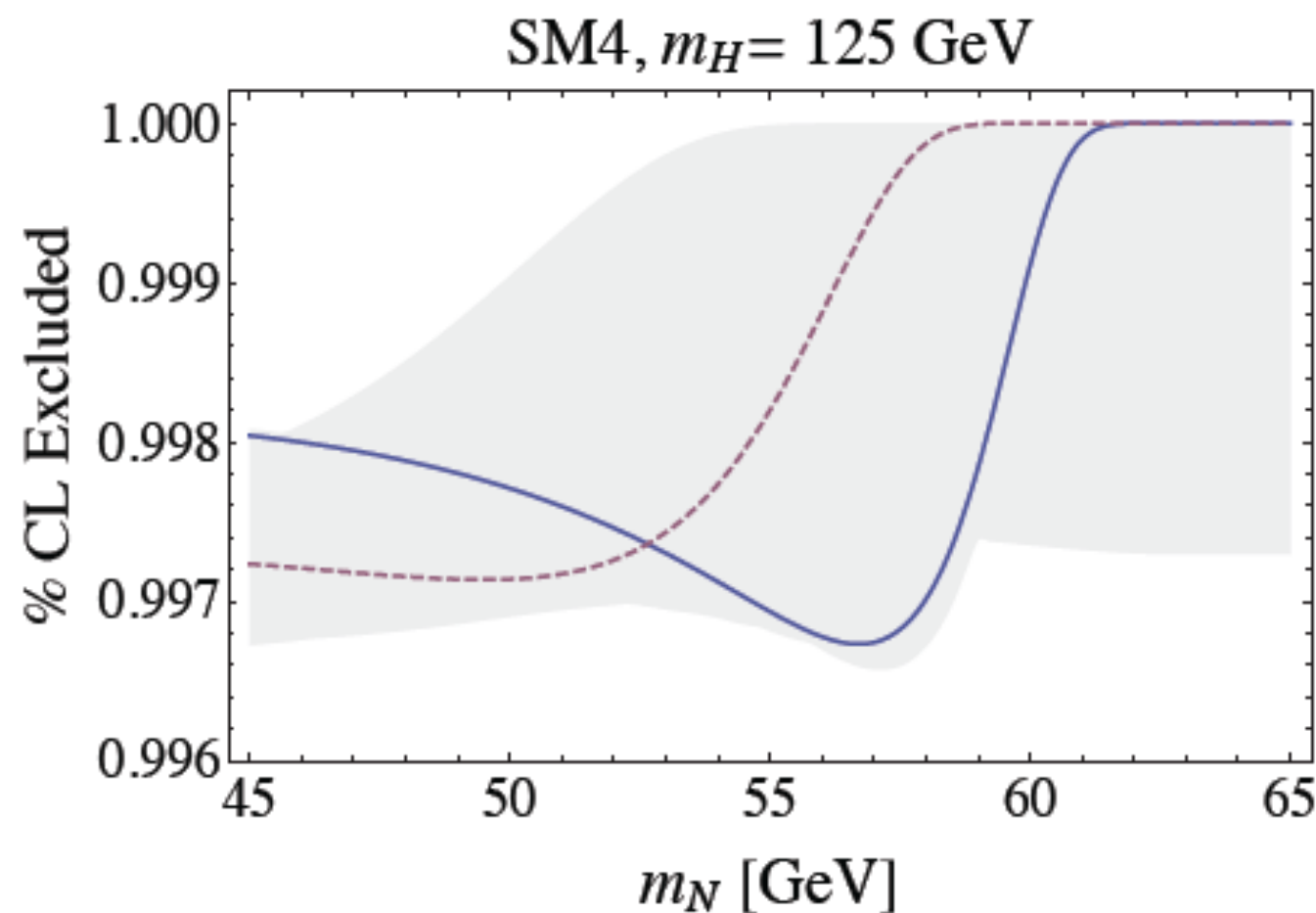
Kuflik, Nir, Volansky 2012

Adjoint Scalar Excluded Region

Adjoint scalar
$G_{4S}(v) = 1$
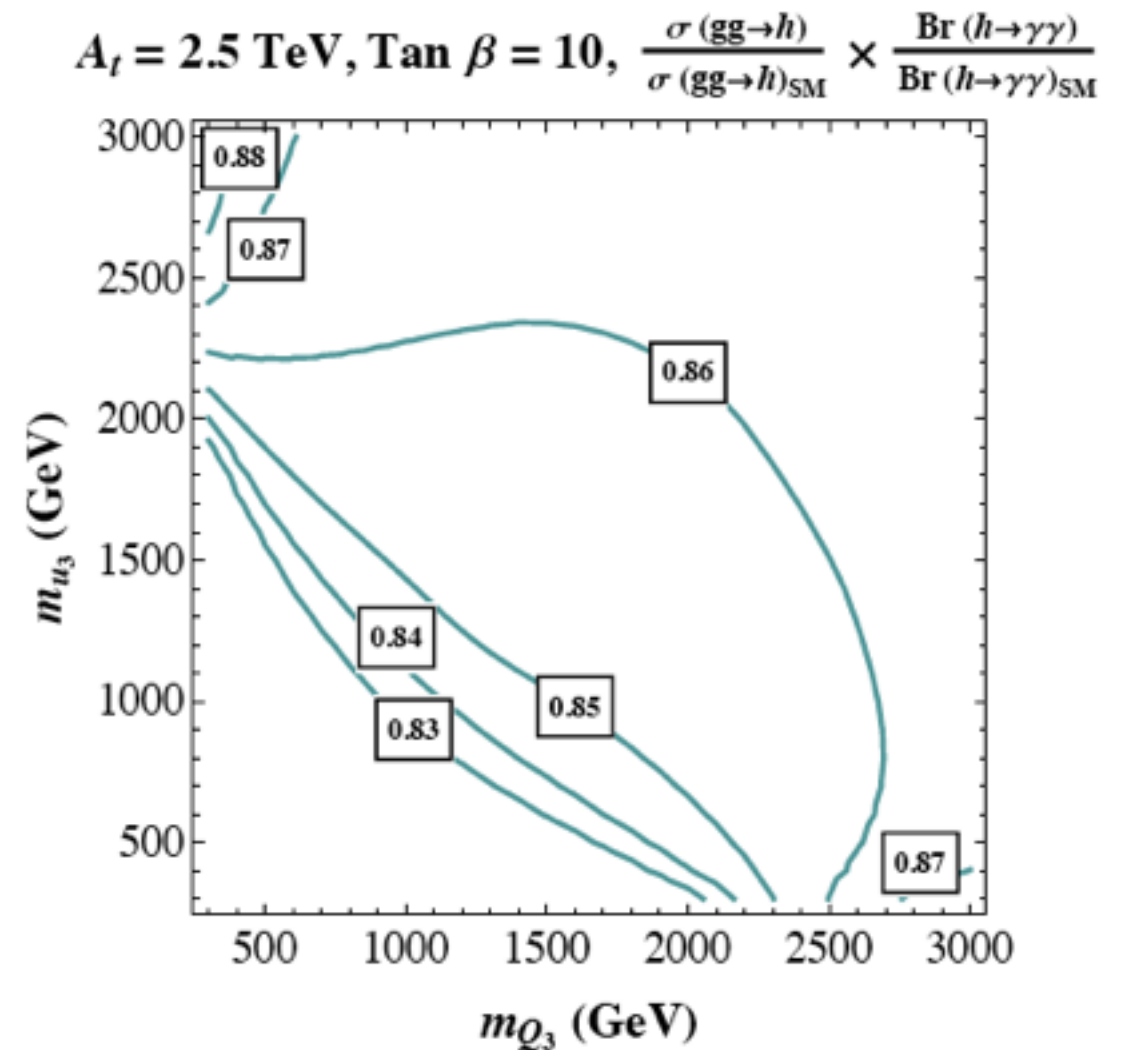$\lambda_1 = 1$

EXCLUDED

R. B. 2011

Measuring Higgs properties

- To pin down the underlying model, what are we interested in measuring?

Angular distributions, of either jets or decay products

Zeppenfeld et al. 2006

$A_t = 2.5$ TeV, Tan $\beta = 10$, $\dfrac{\sigma\,(gg \to h)}{\sigma\,(gg \to h)_{SM}} \times \dfrac{Br\,(h \to \gamma\gamma)}{Br\,(h \to \gamma\gamma)_{SM}}$

The rate

Carena, Gori, Shah, Wagner 2011

Effects of theory uncertainties

- CMS PAS HIG-11-024: (WW channel) "The overall signal efficiency uncertainty... is dominated by the theoretical uncertainty due to missing higher-order corrections"

- ATLAS CERN-PH-EP-2012-013 (γγ): uncertainties due to QCD scale variation one of the two dominant systematic effects (along with photon reconstruction+ID efficiency)

from G. Rolandi, HCP 2011

| Source	Affected Processes	Typical uncertainty
PDFs+α_s (cross sections)	$gg \to H$, $t\bar{t}H$, $gg \to VV$	$\pm 8\%$
	VBF H, VH, VV@NLO	$\pm 4\%$
Higher-order uncertainties on cross sections	total inclusive $gg \to H$	$^{+12\%}_{-7\%}$
	inclusive "gg" $\to H + \geq 1$ jets	$\pm 20\%$
	inclusive "gg" $\to H + \geq 2$ jets	$\pm 20\%$ (NLO), $\pm 70\%$ (LO)
	VBF H	$\pm 1\%$
	associated VH	$\pm 1\%$
	$t\bar{t}H$	$^{+4\%}_{-10\%}$
	uncertainties specific to high mass Higgs boson, see Section 2.1	$\pm 30\%$
	V	$\pm 1\%$
	VV up to NLO	$\pm 5\%$
	$gg \to VV$	$\pm 30\%$
	$t\bar{t}$, incl. single top productions for simplicity	$\pm 6\%$
acceptance	acceptance for $H \to WW \to \ell\nu\ell\nu$ events	$\pm 2\%$
phenomenology	modelling of underlying event and parton showering	$\pm 10\%$
	fake lepton probability ($W + jets \to \ell\ell^{fake}$)	$\pm 40\%$
luminosities	ATLAS and CMS uncertainties on their luminosity measurements	$\pm 3.7\%$, $\pm 4.5\%$

Outline
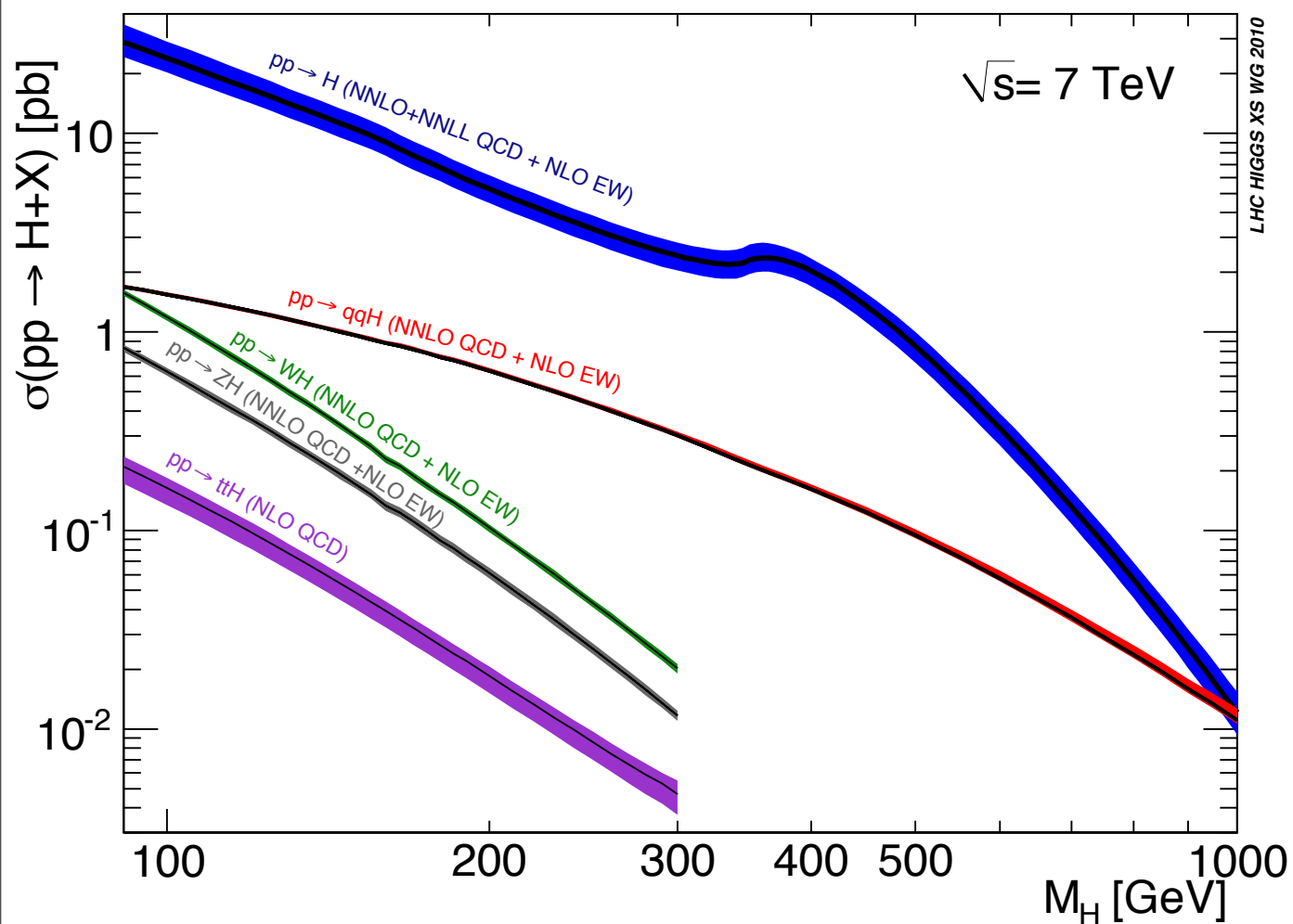
- Review the theory going into the Higgs analysis
- Discuss available tools, some of the tricky points in the calculations
- Brief summary of VH, VBF
- Longer discussion of gluon-fusion and its backgrounds; much recent work and still some unresolved issues in this analysis
- Measurement of Higgs properties

A phenomenological profile
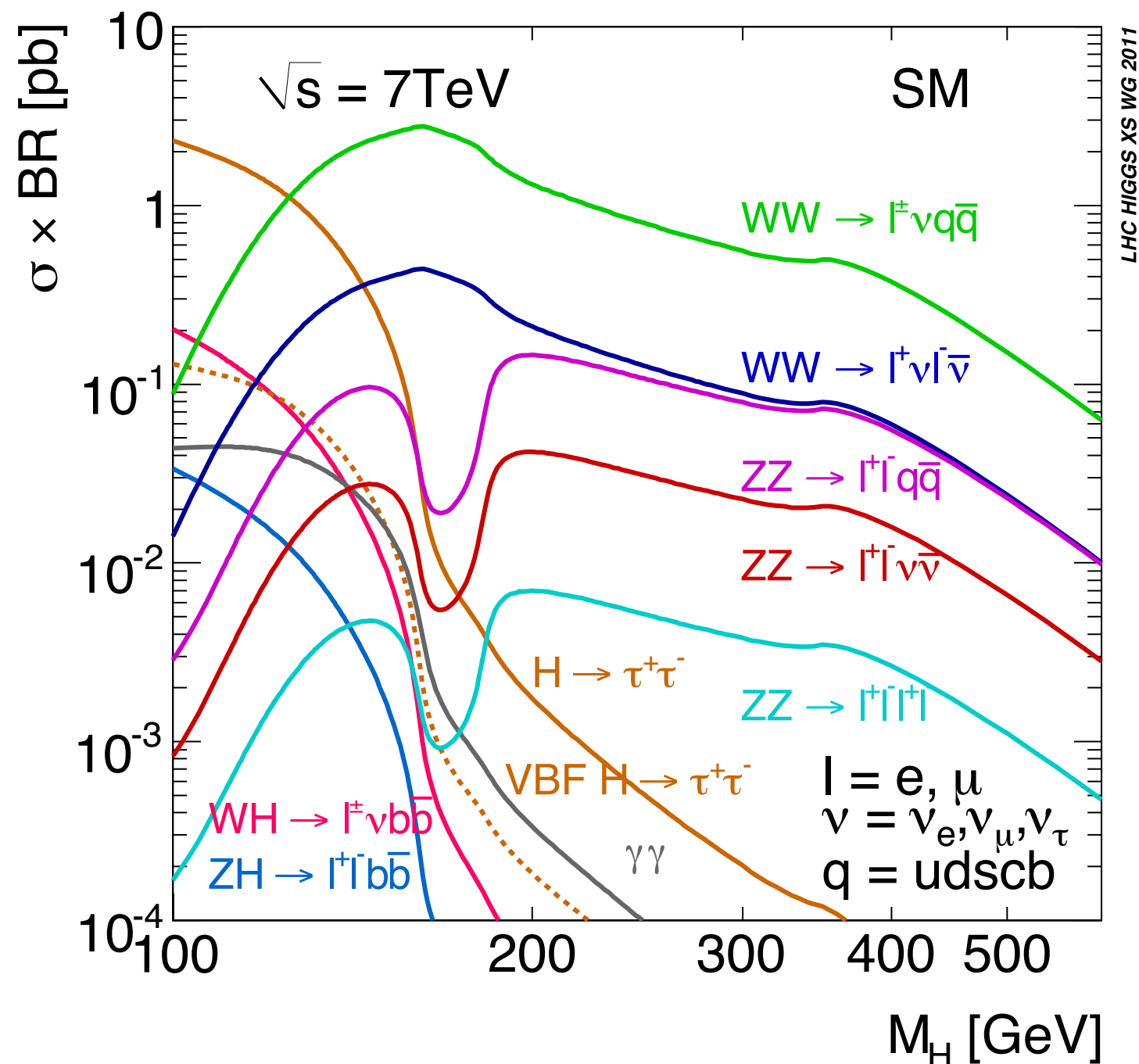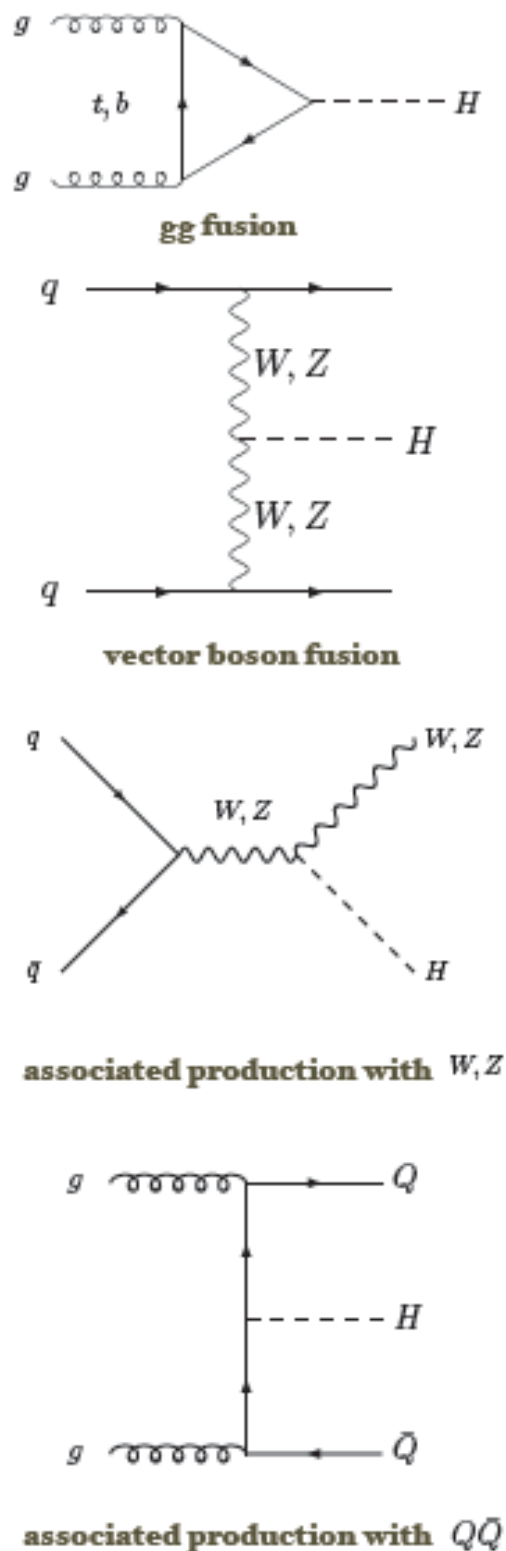
For SM Higgs, production primarily from gg→H, with some contribution from VBF (VH for b Yukawa measurement)

Associated VH production
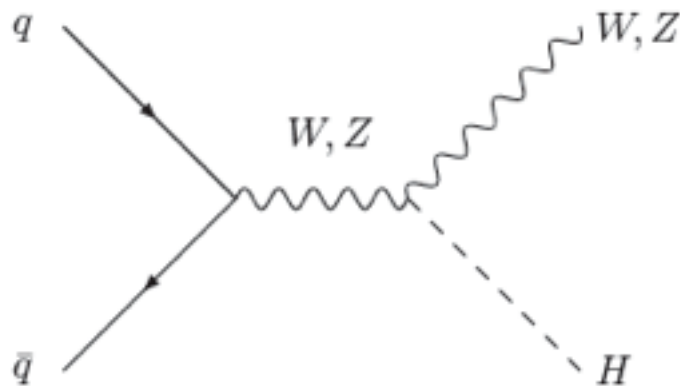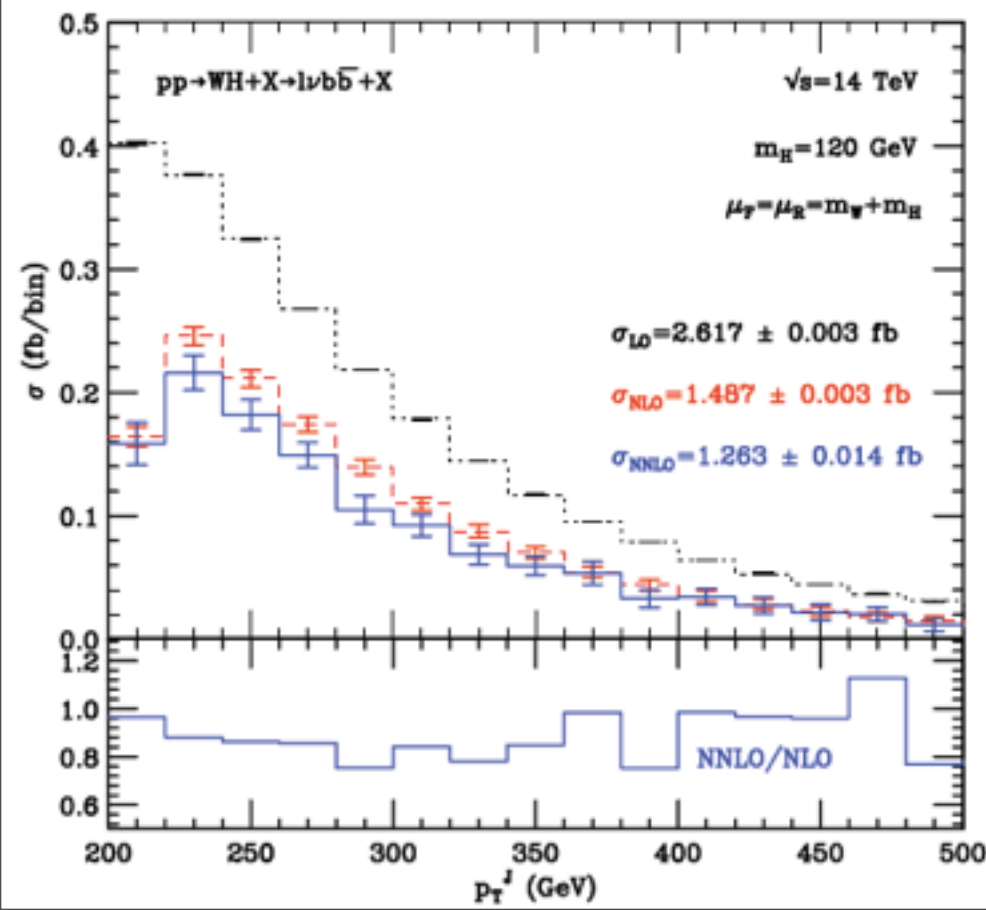

- With bbar decay of Higgs, most important low-mass mode at Tevatron

- At LHC, boosted analysis possible

Butterworth, Davison, Rubin, Salam 2008

Inclusive NLO QCD: +30% (Han, Wllenbrock 1990), NLO EW: +5-10% (Ciccolini, Dittmaier, Denner 2003)

NNLO QCD: 1-2% in bulk of phase space (Ferrera, Grazzini, Tramontano 2011)

$pp \to WH + X \to l\nu b\bar{b} + X$

$\sqrt{s} = 14$ TeV

$m_H = 120$ GeV

$\mu_F = \mu_R = m_W + m_H$

$\sigma_{LO} = 2.617 \pm 0.003$ fb

$\sigma_{NLO} = 1.487 \pm 0.003$ fb

$\sigma_{NNLO} = 1.263 \pm 0.014$ fb

NNLO/NLO

- Original boosted analysis vetoes additional jets to remove ttbar background

- Negative impact on stability of expansion (jet vetoes are theoretically dangerous!)

- Original paper mentions possibility of top-veto instead, likely safer from QCD perspective

Vector boson fusion
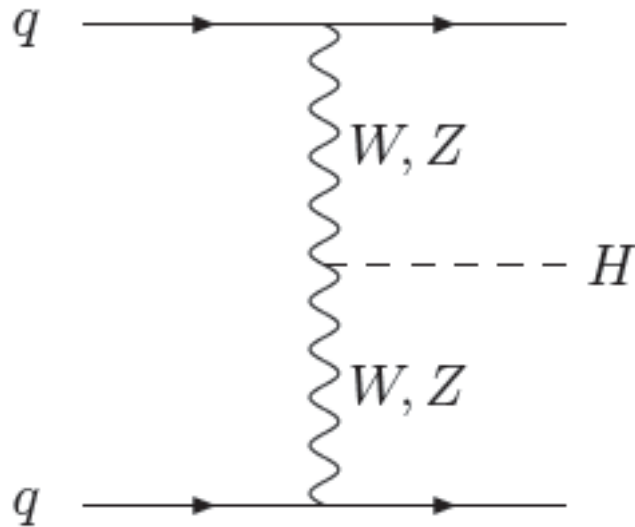
- Important for the low-mass Higgs in both the ττ and γγ modes
- NLO QCD the same as for DIS, increase by 5-10%
- NLO QCD+EW in VBFNLO (Oleari, Zeppenfeld et al., partial EW) and HAWK (Denner, Dittmaier, Mueck, full EW)
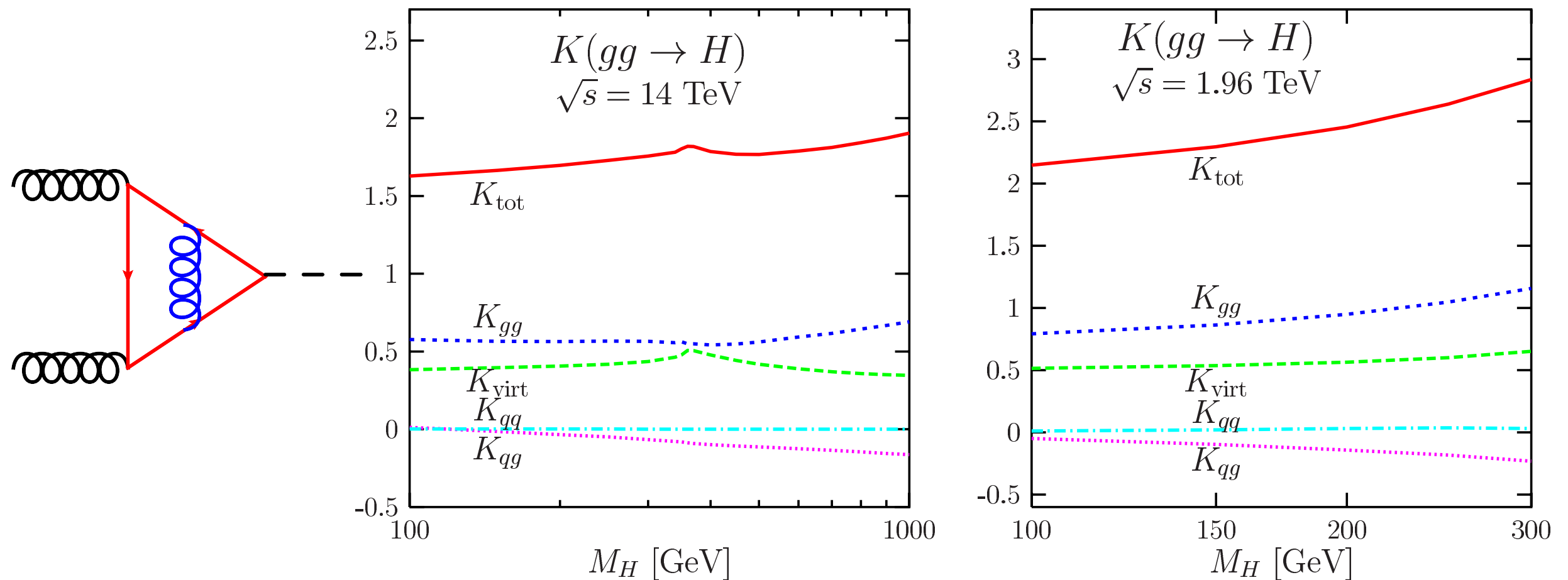
- DIS-like NNLO contributions also calculated, at the percent-level
(Bolzoni, Maltoni, Moch, Zaro 2010)

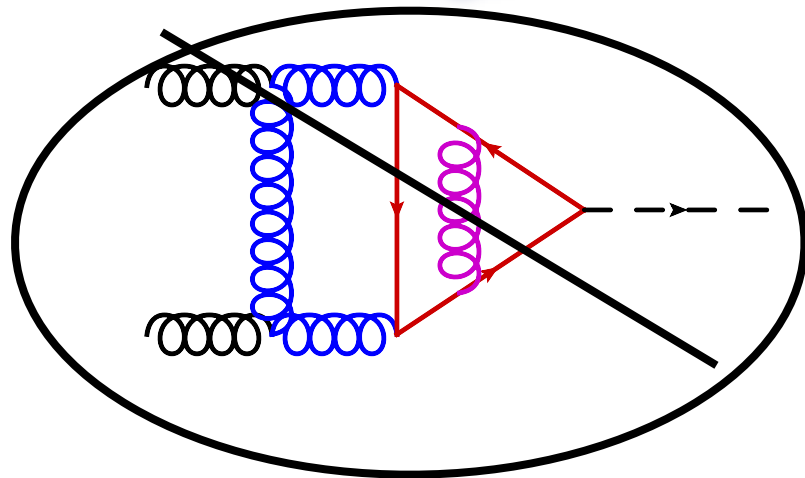- Important distributions under theoretical control
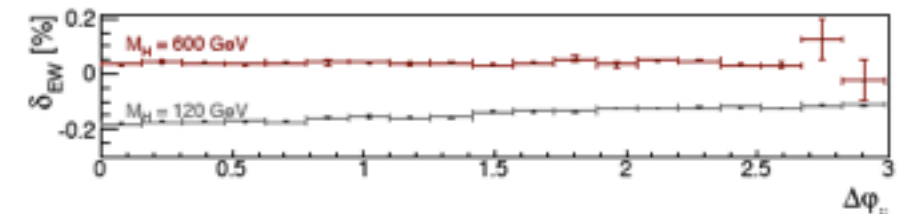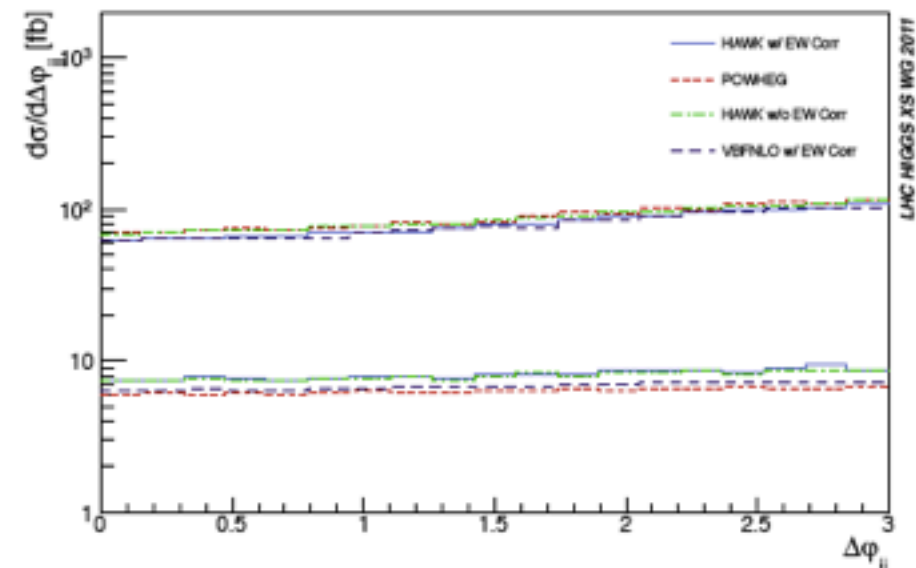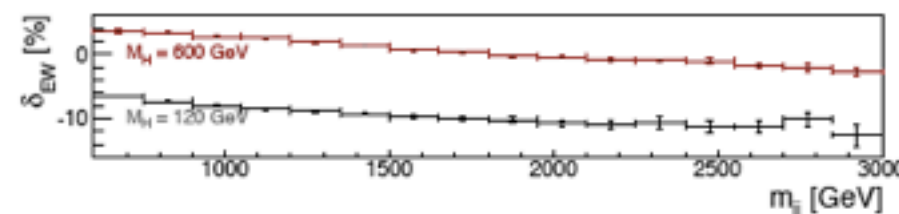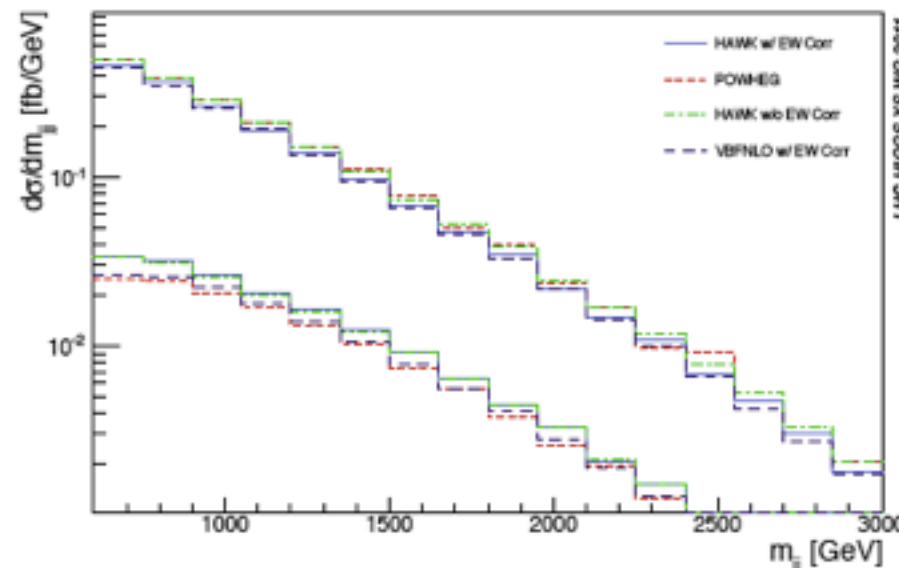
Gluon fusion

- Famously sensitive to large QCD corrections; difficult to calculate to requisite order in perturbation theory. The subject of enormous theoretical effort over the years.
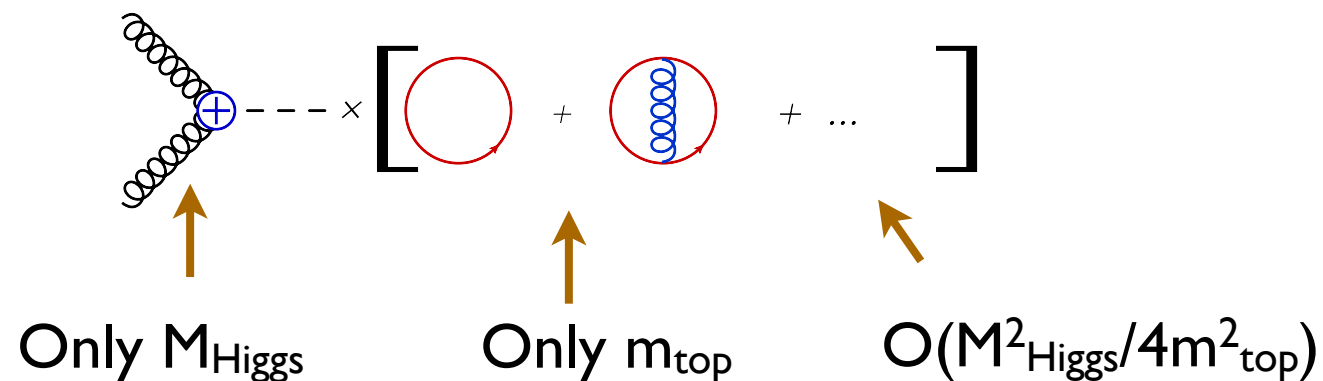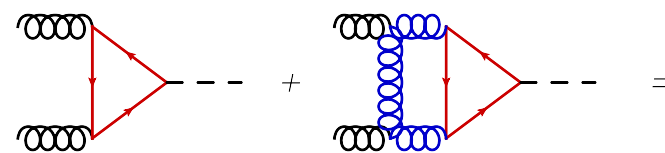

Dawson; Djouadi, Graudenz, Spira, Zerwas, 1991, 1995

Effective interactions

- Getting the next terms requires new techniques
- *Effective field theory*: exploit heavy mass of virtual particles

Two scales:
M_{Higgs}, m_{top}

Only M_{Higgs} Only m_{top} $O(M^2_{Higgs}/4m^2_{top})$

$$\mathcal{L}_{eff} = \alpha_s \frac{C_1}{4v} H \, G^a_{\mu\nu} G^{\mu\nu}_a$$

The Wilson coefficient

$$C_1 = -\frac{1}{3\pi}\left\{1 + \alpha_s C_{1t} + \alpha_s^2 C_{2t} + \lambda_{EW}\left[1 + C_{1w}\right]\right\}$$

W,Z

u,d,c,s,b
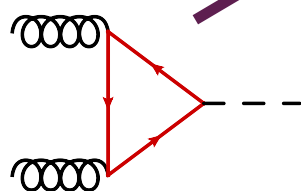
Inami, Kubota, Okada 1982
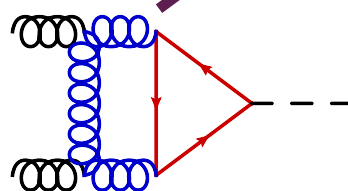
Chetyrkin, Kniehl, Steinhauser 1997
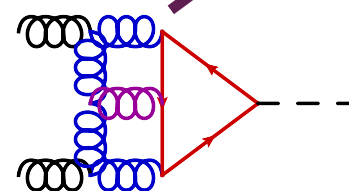
EW terms: Actis, Passarino, Sturm, Uccirati 2008; Anastasiou, R. B., Petriello 2009

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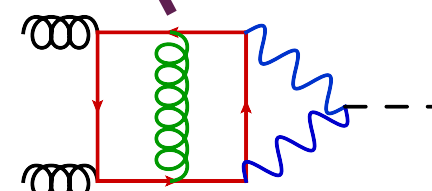
Clear separation of new physics effects into Wilson coefficient, QCD into corrections to the effective vertex

Unreasonably effective EFT

NLO in the EFT:

analytic continuation to time-like form factor

$z = M_H^2/(x_1 x_2 s)$

$$\Delta \sigma = \sigma_0 \frac{\alpha_s}{\pi} \left\{ \left(\frac{11}{2} + \pi^2 \right) \delta(1-z) + 12 \left[\frac{\ln(1-z)}{1-z} \right]_+ - 12z(-z + z^2 + 2)\ln(1-z) \right. $$
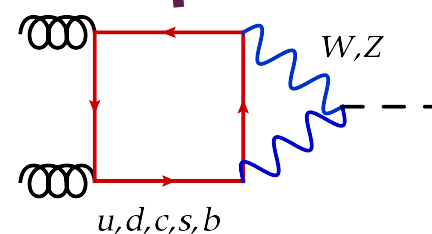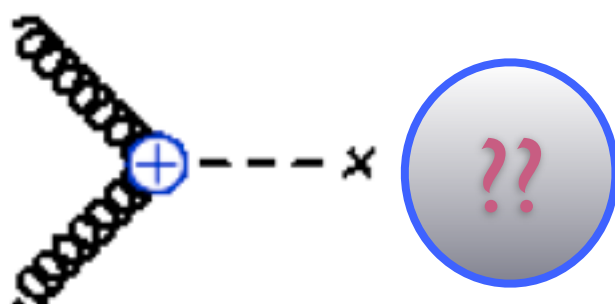$$\left. - 6 \frac{(z^2 + 1 - z)^2}{1-z} \ln(z) - \frac{11}{2}(1-z)^3 \right\}$$

eikonal emission of soft gluons

Identical factors in full theory with $\sigma_0 \rightarrow \sigma_{LO, \text{full theory}}$

$$\boxed{\sigma_{NLO}^{approx} = \left(\frac{\sigma_{NLO}^{EFT}}{\sigma_{LO}^{EFT}} \right) \sigma_{LO}^{QCD}}$$

NNLO study of $1/m_t$ suppressed operators, matched to large s-hat limit, indicates this persists

Harlander, Mantler, Marzani, Ozeren; Pak, Rogal, Steinhauser 2009

error of 10% on 100% correction
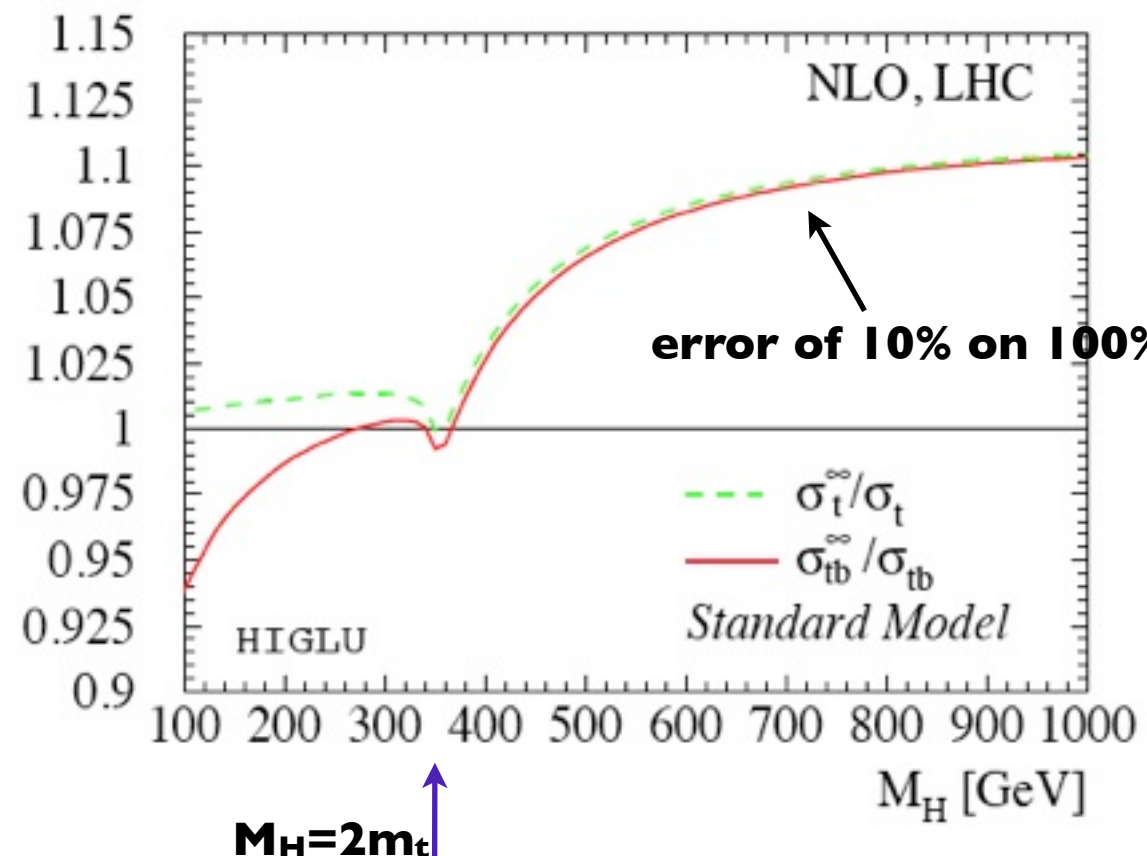
NNLO in the EFT

- Success of the EFT over almost entire interesting mass range motivates NNLO calculation

FEHiP: Anastasiou, Melnikov, Petriello 2005

Harlander, Kilgore; Anastasiou, Melnikov;
Ravindran, Smith, van Neerven 2002-2003
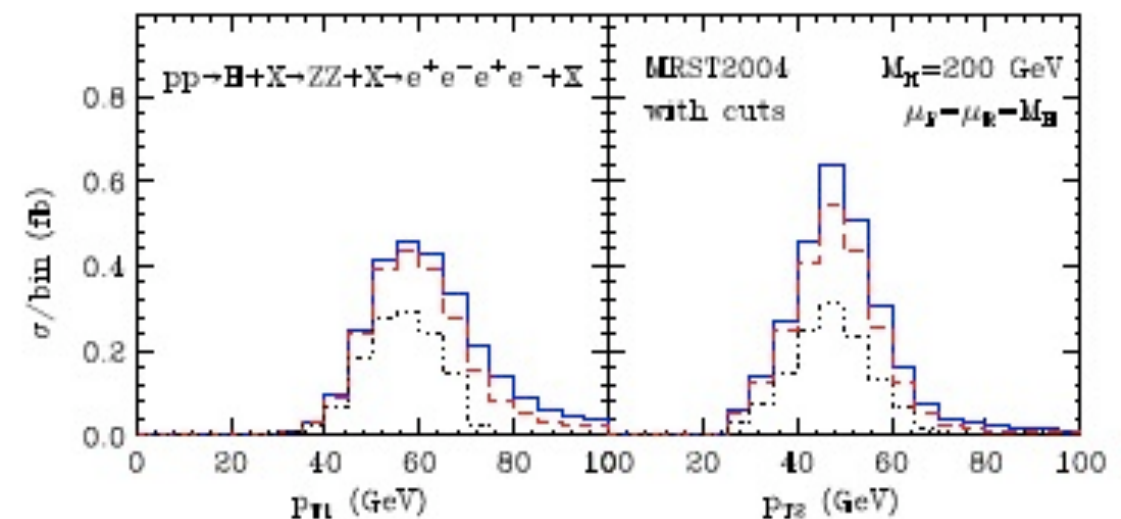
HNNLO: Catani, Grazzini 2007-2008

Gluon-fusion: inclusive

Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about 6-15%)

S. Catani, D. De Florian, P. Nason, Grazzini (2003)

Partial N^3LO corrections known (considerably reduced scale dependence)

Moch, Vogt (2005)

Two-loop EW corrections are also known (effect is about O(5%))

U. Aglietti et al. (2004)
G. Degrassi, F. Maltoni (2004)
G. Passarino et al. (2008)

Mixed QCD-EW effects evaluated in EFT approach

Anastasiou, R. B. , Petriello (2008)

→ support "complete factorization": EW correction multiplies the full QCD corrected cross section

Keung, Petriello, (2009)
O. Brein, (2010)

EW effects for real radiation (effect O(1%))

The jet-veto in gluon fusion

ATLAS Preliminary — H→WW (m_H=170 GeV), Data, W+jets, WW, WZ/ZZ/Wγ, top, Z/γ+jets. $\sqrt{s}$ = 7 TeV, $\int L\,dt = 35\ pb^{-1}$. Jet multiplicity.
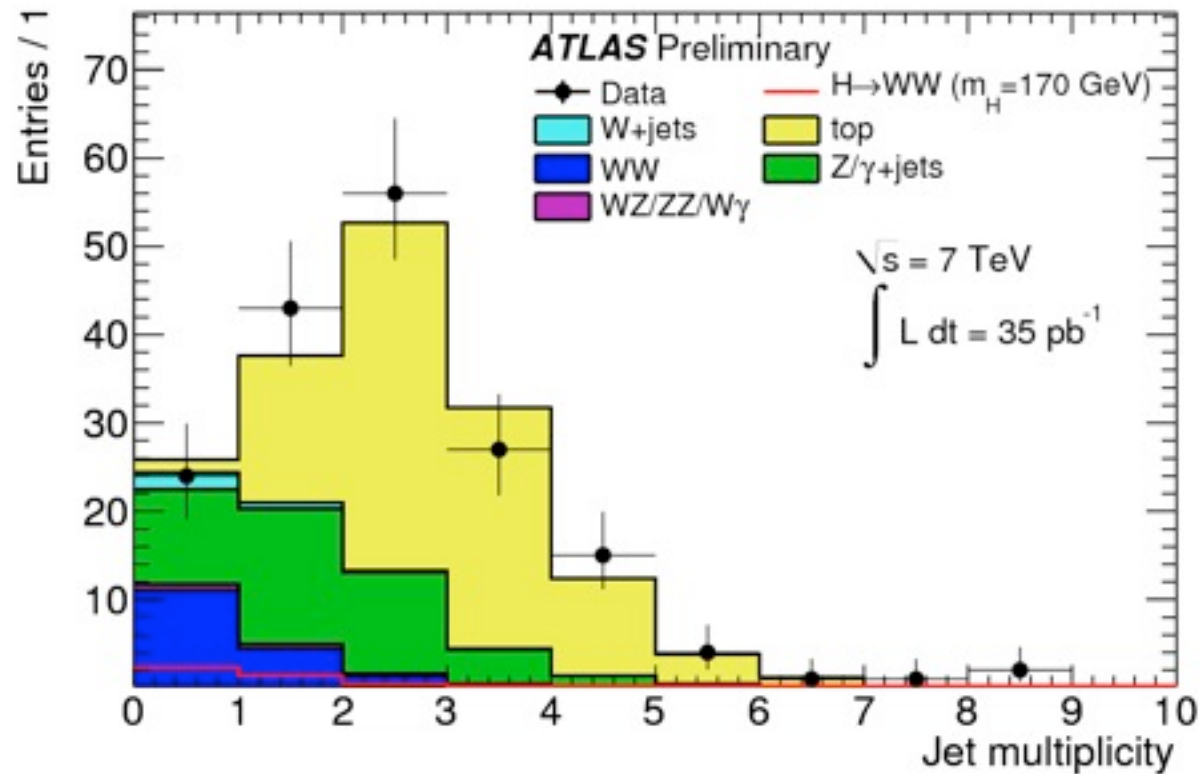
- Toughest cut from theoretical perspective is the jet veto
- Required in WW channel due to background composition; also used in other channels to improve S/B
- 25-30 GeV jet cut used; restriction of radiation leads to large logs

MRST2004 (N)NLO, $m_H/2 \leq \mu_R = \mu_F \leq 2\,m_H$, m_H = 165 GeV. R(MC@NLO), NNLO. σ_{cum} [fb] vs p_T^{veto} [GeV]. Anastasiou, Dissertori, Stoeckli 2007
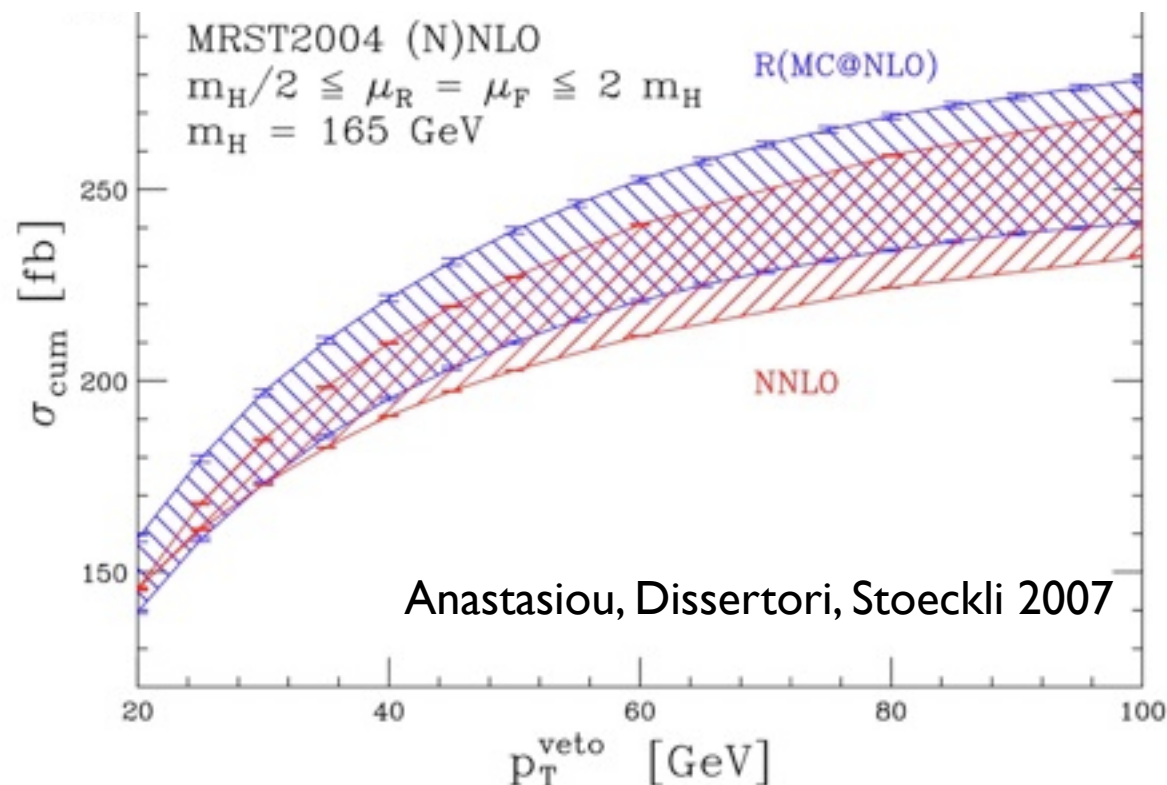
- Inclusive scale variation 10%; with a 25 GeV jet veto, 5-6%!
- Having $\Delta\sigma_{veto} < \Delta\sigma_{tot}$ doesn't seem correct; σ_{veto} has a more complicated structure and a larger expansion parameter, $\alpha_S \ln^2(m_H/p_{T,cut})$ rather than α_S

Cancellations

- Study of cross section structure (Stewart, Tackmann 2011)

$$\sigma_0(p^{\text{cut}}) = \sigma_{\text{total}} - \sigma_{\geq 1}(p^{\text{cut}})$$

$$\simeq \sigma_B\Big\{ \big[1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)\big] - \big[\alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \mathcal{O}(\alpha_s^3 L^6)\big]\Big\}$$

$$\sigma_{\text{total}} = (3.32\,\text{pb})\big[1 + 9.5\,\alpha_s + 35\,\alpha_s^2 + \mathcal{O}(\alpha_s^3)\big]\,,$$

$$\sigma_{\geq 1}\big(p_T^{\text{jet}} \geq 30\,\text{GeV},\, |\eta^{\text{jet}}| \leq 3.0\big) = (3.32\,\text{pb})\big[4.7\,\alpha_s + 26\,\alpha_s^2 + \mathcal{O}(\alpha_s^3)\big]\,.$$

- Accidental cancellation between large corrections to total cross section and logarithms, leading to reduced scale error. No reason to persist at higher orders

Explicit demonstration

- Further evidence: three ways of extending the calculation of the 0-jet event fraction that differ by $O(\alpha_S^3)$ w.r.t. leading order

LHC, 7 TeV
HNNLO + MCFM
$M_H/4 \le \mu_R, \mu_F \le M_H$
$1/2 \le \mu_R/\mu_F \le 2$

scheme (a)
scheme (b)
scheme (c)
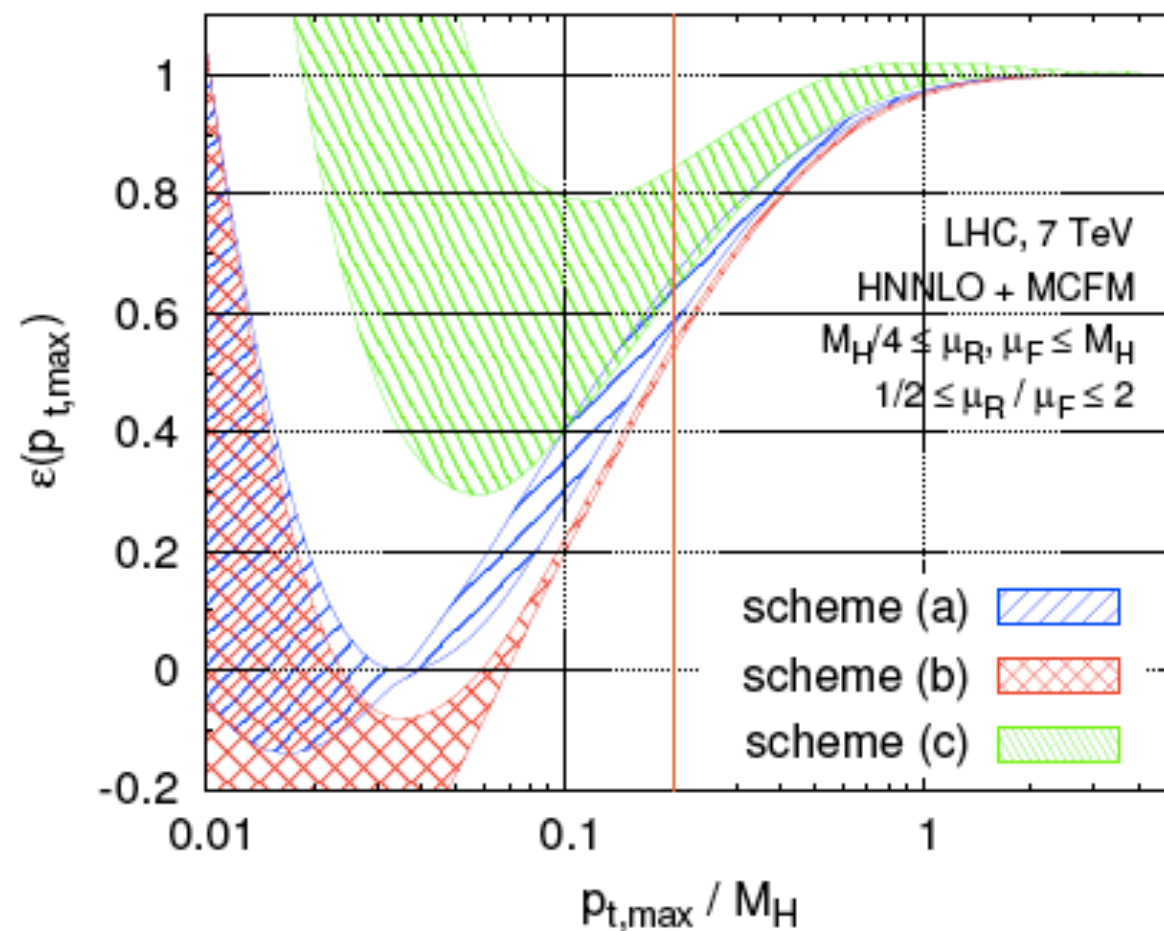
Banfi, Salam, Zanderighi 2012

$$f_0^{(a)}(p_T^{cut}) \equiv \frac{\Sigma^{(0)}(p_T^{cut}) + \Sigma^{(1)}(p_T^{cut}) + \Sigma^{(2)}(p_T^{cut})}{\sigma^{(0)} + \sigma^{(1)} + \sigma^{(2)}}$$

$$f_0^{(b)}(p_T^{cut}) = 1 - \frac{\sigma_{1\text{-jet}}^{NLO}(p_T^{cut})}{\sigma^{(0)} + \sigma^{(1)}} .$$

$$f_0^{(c)}(p_T^{cut}) = 1 - \frac{\sigma_{1\text{-jet}}^{NLO}(p_T^{cut})}{\sigma^{(0)}} + \frac{\sigma^{(1)}}{(\sigma^{(0)})^2}\sigma_{1\text{-jet}}^{LO}(p_T^{cut})$$

- Gives results differing from 0.5 to 0.85 for a 30 GeV veto

Error prescription

- A solution using fixed-order results was pointed out (Stewart, Tackmann 2011)

- In the limit of $\ln(m_H/p_{T,cut})$ large, σ_{tot} and $\sigma_{\geq 1}$ have independent expansions

- Gives expected result, that $\Delta\sigma_{veto} > \Delta\sigma_{tot}$

- The current prescription used in LHC analyses (phrased in terms of jet fractions)

First consider *inclusive* jet cross sections

$$\sigma_{\text{total}},\ \sigma_{\geq 1},\ \sigma_{\geq 2} \quad \Rightarrow \quad C = \begin{pmatrix} \Delta^2_{\text{total}} & 0 & 0 \\ 0 & \Delta^2_{\geq 1} & 0 \\ 0 & 0 & \Delta^2_{\geq 2} \end{pmatrix}$$

Transform to *exclusive* jet cross sections

$$\sigma_0 = \sigma_{\text{total}} - \sigma_{\geq 1}, \qquad \sigma_1 = \sigma_{\geq 1} - \sigma_{\geq 2}, \qquad \sigma_{\geq 2}$$

$$\Rightarrow \quad C = \begin{pmatrix} \Delta^2_{\text{total}} + \Delta^2_{\geq 1} & -\Delta^2_{\geq 1} & 0 \\ \Delta^2_{\geq 1} & \Delta^2_{\geq 1} + \Delta^2_{\geq 2} & -\Delta^2_{\geq 2} \\ 0 & -\Delta^2_{\geq 1} & \Delta^2_{\geq 2} \end{pmatrix}$$

cut	$\dfrac{\Delta\sigma_{\text{total}}}{\sigma_{\text{total}}}$	$\dfrac{\Delta\sigma_{\geq 1}}{\sigma_{\geq 1}}$	$\dfrac{\Delta\sigma_{\geq 2}}{\sigma_{\geq 2}}$	$\dfrac{\Delta\sigma_0}{\sigma_0}$	$\dfrac{\Delta\sigma_1}{\sigma_1}$
$p_T^{\text{cut}} = 30\,\text{GeV},\ \eta^{\text{cut}} = 3$	10%	21%	45%	17%	29%

Jet-veto resummed

- Recent NLL resummation of the jet-vetoed cross section

  Banfi, Salam, Zanderighi 2012

Higgs production (m_H = 125 GeV), NNLO v. NLL+NNLO

pp, 7 TeV
$m_H/4 < \mu_{R,F}, Q < m_H$, 3 schemes
MSTW2008 NNLO PDFs
anti-k_t, R=0.5

NNLO
NLL+NNLO

$\epsilon(p_{t,veto})$

$\epsilon(p_{t,veto}) / \epsilon_{central}(p_{t,veto})$

$p_{t,veto}$ [GeV]
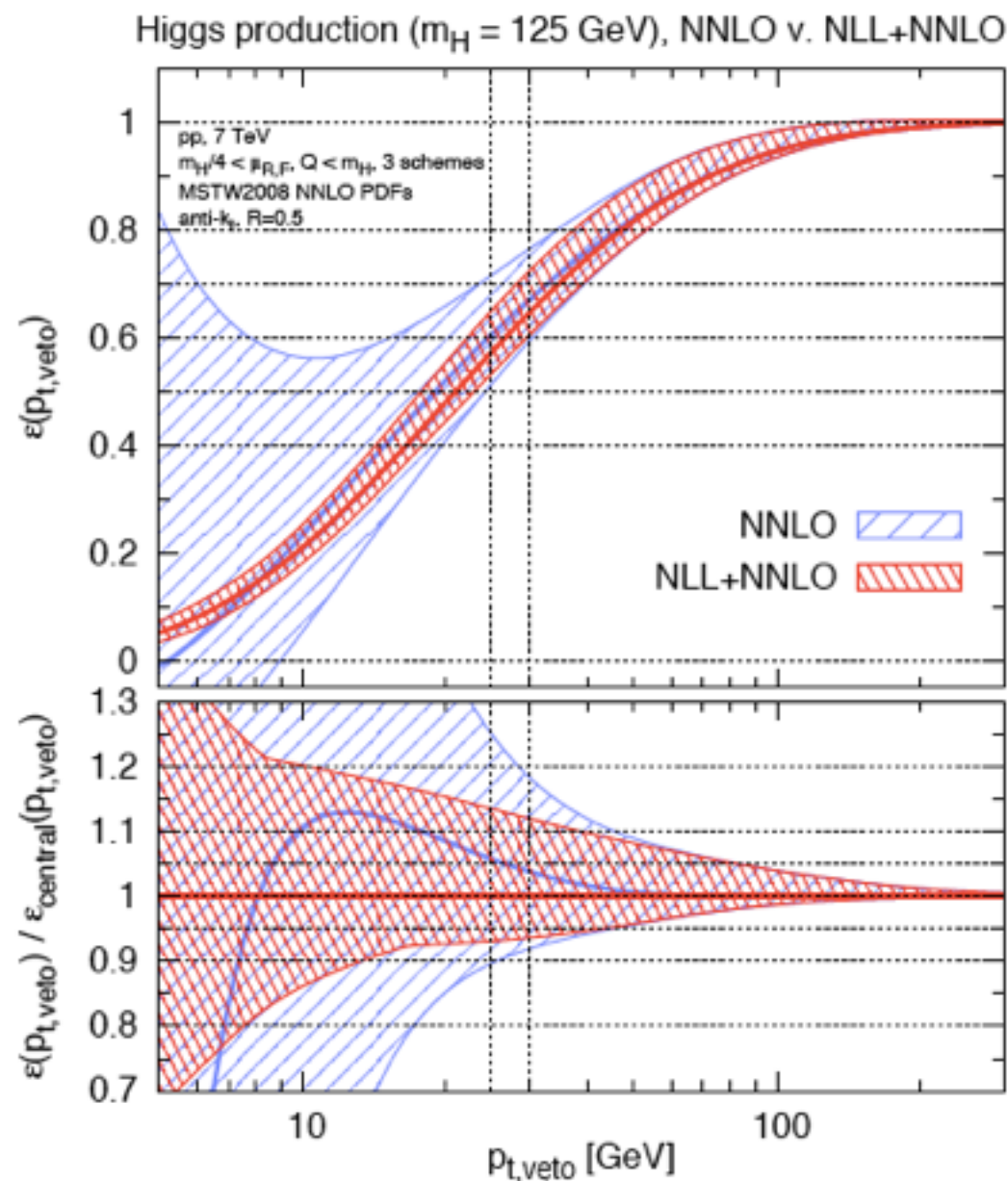
- Numbers not much reduced from those estimated using previous prescription (error defined here as envelope of methods a, b, c from before)

- Very recent attempts to extend this to NNLL by two groups: Banfi, Monni, Salam, Zanderighi; Becher, Neubert

It is an area of active debate whether this is possible: Walsh, Tackmann, Zuberi

Analyzing Higgs properties

Studying the Higgs properties using single variable asymmetries

- First establish the spin and CP properties of the new resonance; let's make sure it's the Higgs!

- In H -> ZZ -> 4l, with lepton-pair invariant masses M_{12} and M_{34}, the threshold behavior differs for various spin/CP combinations as M_{34} approaches its maximum $M_H - M_{12}$
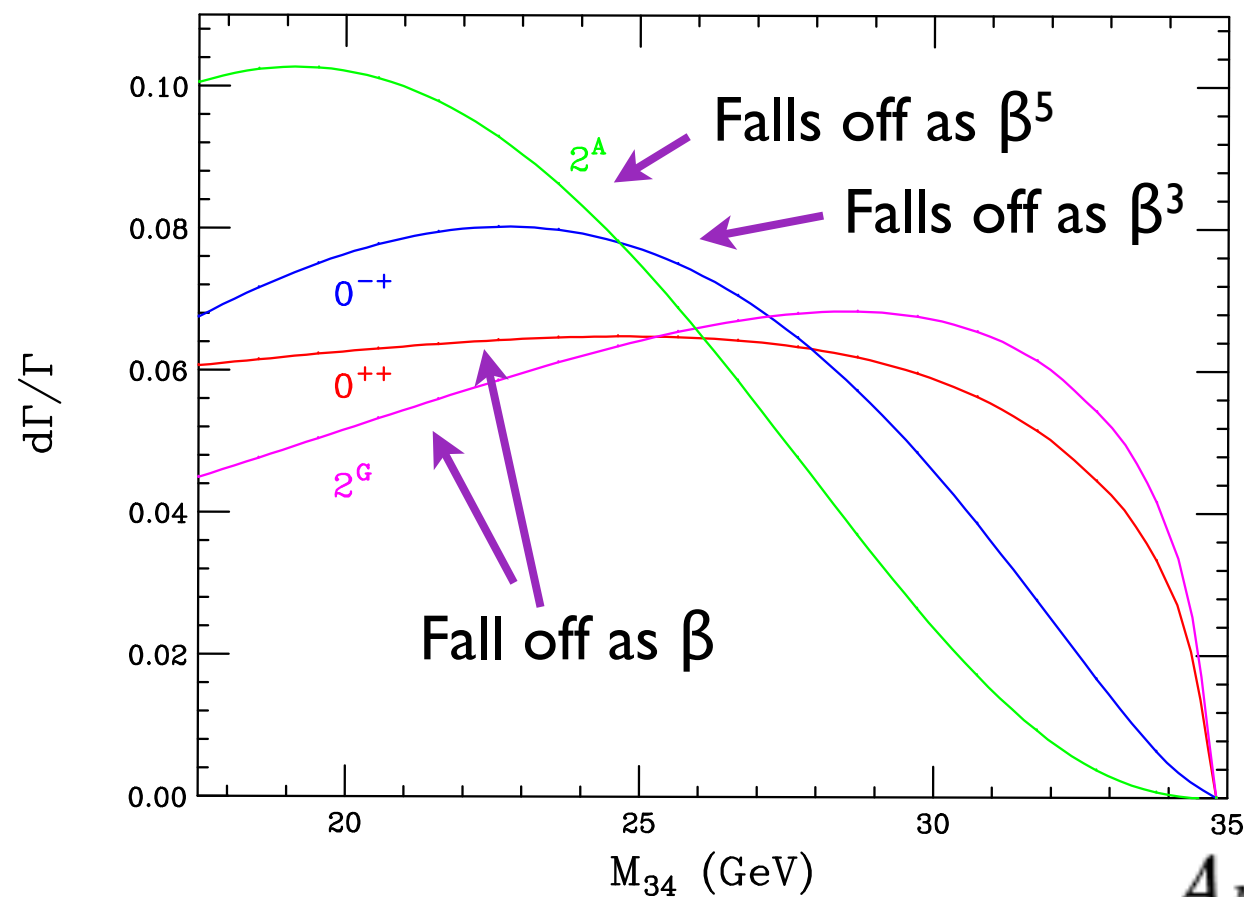
β=momentum of 34 system in Higgs rest frame

- A simple asymmetry captures this difference in shape:

R. B., LeCompte, Petriello arXiv:1208.4311

$$\mathcal{A}_{M_{cut}} = \frac{N(M_{34} > M_{cut}) - N(M_{34} < M_{cut})}{N(M_{34} > M_{cut}) + N(M_{34} < M_{cut})}$$

Studying the Higgs properties using single variable asymmetries

- **Results with one handful of events:** R. B., LeCompte, Petriello arXiv:1208.4311

Consider an initial study of ATLAS+CMS events consistent with ZZ^* production. This is just 10 events, with half expected to be background! Note that the extension to Z^*Z^* is not difficult, not done here for simplicity of M_{cut} choice.

$$\mathcal{A}_{26}^{sig+back}(0^{++}) = -0.060, \quad \mathcal{A}_{26}^{sig+back}(2^A) = -0.31 \qquad A_{26}(\text{data}) = 0\pm0.28$$

$\Rightarrow$ already disfavor 2^A at the 1-σ level

$$\mathcal{A}_{28}^{sig+back}(0^{++}) = -0.31, \quad \mathcal{A}_{28}^{sig+back}(0^{-+}) = -0.44 \qquad A_{28}(\text{data}) = -0.40\pm0.27$$

$\Rightarrow$ data uncertainty too large right now, need more luminosity

- The method has the advantage of simplicity, ease of application with the initial data, and ability to trivially combine ATLAS and CMS data
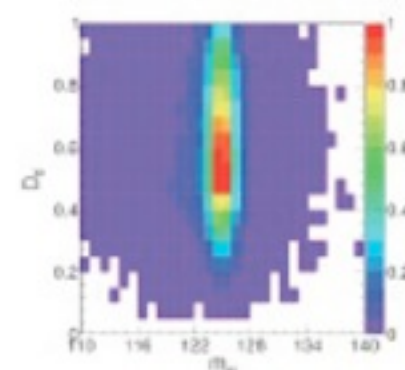
Studying the Higgs properties using MELA

● Spin and parity are explored through angular analysis of Higgs decay products in H -> WW, ZZ, gamma gamma

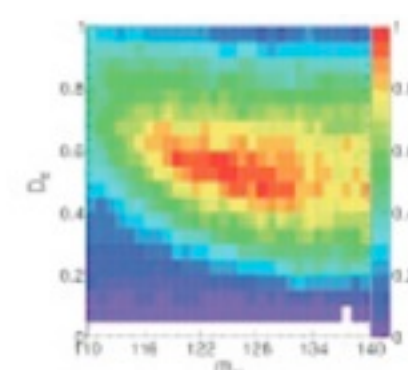●To enhance hypothesis separation, a multi-variate analysis (MELA) was developed
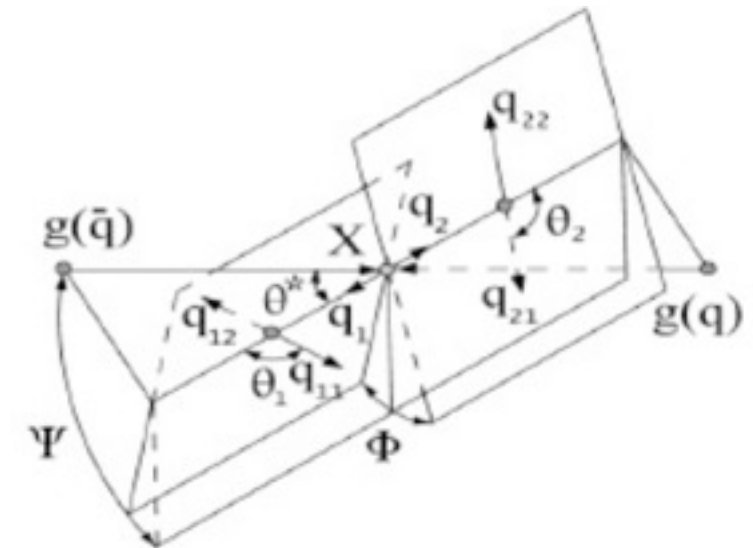
2-dim. analysis
MELA vs. m$_{4l}$
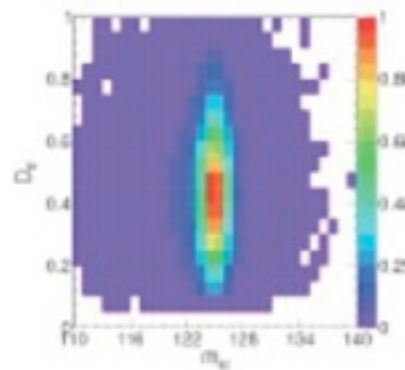
SM Higgs   spin-0 pseudoscalar   SM background

Expected separation significance (Gaussian σ) for 35 fb^{-1} integrated luminosity at the 8 TeV LHC

scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0_m^+ vs background	7.1	4.5	5.2	9.9
0_m^+ vs 0^-	4.1	1.1	0.0	4.2
0_m^+ vs 2_m^+	1.6	2.5	2.5	3.9

JHU generator
Bolognesi et al

Summary

- We have moved beyond the discovery stage of the Higgs and begun analyzing the discovered particle

- SM predictions for the Higgs are the benchmark against which all other possibilities will be compared

- After years of work by a large community, predictions under fairly good control

- The few lingering issues occur in the interplay of experimental cuts with QCD. In general, one has to be careful with jet vetoes

- Many tools exist; recent new ones for both signal and background

- We're prepared for the next stage after discovery!

Higgs excitement has just begun, sketching the Higgs's face will require a lot of theoretical and experimental hard work!